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DATA AVAILABILITY, DATA QUALITY IN LCA

Knowledge diffusion and collaboration networks on life cycle assessment

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Abstract
Purpose The interest in life cycle assessment (LCA) studies has increased over the years, and one of the main ways of disseminating these studies is through the publication of articles in scientific journals. Coauthorship relations form a social network where it is possible to identify how research is organized and structured in a specific field of knowledge. This paper aims to show the spread of these studies and the configuration of a collaboration network based on coauthorship relations between researchers of LCA considering some properties of social networks.
Methods The research was based on a bibliometric approach of 1,386 articles related to LCA and published in journals indexed in the ISI/Web of Science until 2008. A free software, Pajek, which has been largely used for the representation and analysis of social networks, was employed in this work. The properties of social networks analyzed in this study were power law, degrees of separation, giant component, and clustering.
Results and discussion The research showed a social network formed by 2,598 authors from 60 countries, 88% of coauthored articles, a mean of 1.87 authors per article; the distribution of articles per author follows a power law ($f(z)=2{,}134.3\times z^{-2.544}$) with a high regression coefficient ($R^2=0.9704$), a degree of separation of 6.5, a giant component embracing 37% of the authors, and a clustering coefficient of 0.75. The LCA coauthorship network has properties following power law patterns similar to other nets such as WWW. The community forms a giant component which is still small, but which, nevertheless, might experience considerable growth in the near future. The average distance between authors follows the small-world hypothesis. The clustering degree was also coherent with other scientific communities.
Conclusions In spite of being an area with less than 20 years of publications registered in the ISI/Web of Science, LCA is now experiencing fast dissemination involving a large number of articles, authors, and institutions. The LCA's coauthorship network can be characterized as a scientific community with properties verified in other networks of more consolidated academic collaboration.

Keywords Life cycle assessment · Social network analysis · Bibliometrics

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1 Introduction

The interest in life cycle assessment (LCA) studies has increased in academic, manufacturing, and government environments. Standards such as ISO 14040 and 14044 are stimulating the adoption of practices aimed at life cycle analysis to guide decision making on products and processes which are less harmful and damaging to the environment. The role of organizations as national LCA societies, the UNEP/SETAC Life Cycle Initiative, and the Society for Industrial Ecology, governmental bodies as EU Commission and national environmental agencies like Environmental Protection Agency, and moreover industries have also largely contributed to the dissemination of LCA studies.

One of the main ways of disseminating the research findings and case studies related to LCA is through the publication of articles in scientific journals. These publications complete the scientific communication cycle (research–dissemination–reading–validation and peer acceptance–research) promoting the progress of science through the generation of new knowledge or use of produced knowledge (Oliveira 2005). According to Klöpffer (2007), “Modern science and publishing requires enough information to repeat experiments and to fully understand theories.”

Scientific articles are an important source of information in order to identify the development of knowledge and pinpoint how research is organized and structured in a field of knowledge based on coauthorship relations. Since the 1960s, studies on coauthorship have been carried out focusing on the development of methodologies and analyses to better understand this social phenomenon, which, on the whole has intensified in all areas of knowledge. The practice of writing articles with multiple authors is relatively recent and has intensified in the last decades (Acedo et al. 2006). This increase of coauthorship has occurred in incidence (a fraction of articles written in partnership) and in length (number of coauthors by publication) (Laband and Tollison 2000).

The increase of articles with multiple authors can be explained by the following reasons: the presence of new collaborative tools, which favor this kind of work; government funding, which stimulates the cooperation between institutions (Hou et al. 2008; Kretschmer 2004; Lee and Bozeman 2005); high R&D costs; the need for specialization; and, finally, the interdisciplinary character of contemporary science (Lee and Bozeman 2005).

According to Kuhn (2006), each scientific community shares generalizations, methods, beliefs, values, and historical context that lead to a convergence of judgments into the social group, and of which only has access through a socialization process in the environment of that community. This dissemination provides the scientific community with the fundamentals of the research practice and serves, for a time, to define the problems and legitimate methods of a research field for succeeding generations of practitioners of science. Mattedi and Spiess (2010) say that the production and transmission of scientific knowledge is a social activity that involves integrating a cultural community. They indicate that the effects of the process of integration and operation of the scientific community impact in the teaching–learning relations (education) and the social context (society). In this integration, the socialization processes into the scientific community not only transmit technical skills, but also normative commitments.

Balancieri et al. (2005) say that scientific collaboration can be seen as a cooperative enterprise which deals with common goals, coordinated efforts, and objective outcomes or products, and with shared responsibilities and merits. It offers an opportunity for improving results and maximizing the potentials of scientific production. Although scientific collaboration can occur through formal or informal relations, coauthorship is one of the main ways of measuring acquaintances among researchers (Cronin et al. 2003; Laband and Tollison 2000).

Coauthorship relations form a social network which can be represented by a graph. Each vertex represents an author, and the edges correspond to connections between these authors through partnership publications. Several authors, such as Newman and Watts (1999); Barabási et al. (2002); Goyal et al. (2006), and more recently Goldenberg et al. (2010) Yan et al. (2010), studied the progression and structure of these graphs using social network analysis (SNA). SNA deals with the relations of actors in network, not only on their attributes. Through SNA, it is possible to identify relationship patterns, connectivity, cluster formation, information flows, and the network evolution through time.

Some collaboration graph characteristics follow power laws. A graph following a power law means that a small number of vertices (authors) has many interactions with other vertices while a large number of authors has few interactions. In other words, social networks follow functions of the type:

$$f(z) = k \times z^{-\tau}$$

Albert et al. (1999) and Barabási et al. (2002), among others, have been also verifying the occurrence of power laws in several graphs. Their studies have focused mainly on factors governing the links distribution in the World Wide Web or the degrees distribution in coauthorship graphs.

The appearance of a giant component is also common. A giant component corresponds to a subnet formed by the largest share of vertices (authors) interconnected within a network. Furthermore, the existence of a giant component means that it is possible to reach a large number of other authors of the same graph starting by one of the vertices and moving along the edges. In general, a coauthorship network starts with several local associations forming little communication groups between members. As the total number of connections increases, these groups also start to form connections between them, and, at some point, a giant connex component linking the vertices is built. In some areas, this connection embraces more than 90% of the vertices (Newman 2001).

It was verified that in several social networks, the average distance between two vertices taken at random was very small (around six, in several references (Milgram 1967; Newman and Watts 1999; Goyal et al. 2006). A small average distance between the vertices means that the

Table 1 Dissemination of articles about LCA

Period Years	I 1993–1996	II 1997–2000	III 2001–2004	IV 2005–2008	Total
Articles	41	147	370	828	1,386
Areas	21	57	61	67	90
Journals	26	81	116	160	305
Countries	11	21	41	55	60
Institutions	45	158	368	540	1,102
Authors	101	360	953	2,234	2,598

community represented by the graph fits the small-world hypothesis.

Real social networks tend to present more clusters of vertices than a purely random network (Barabási et al. 2002). A network of coauthors presenting a high degree of clustering means there is a high probability of partners of an author being also coauthors between them. These clusters can represent local knowledge communities (Newman 2001). At first sight, this clustering may seem to contradict the small-world hypothesis. However, Watts and Strogatz (Watts and Strogatz 1998) studied this phenomenon and showed that the inclusion of some random edges induces the small-world property in a highly clustered social network. They proposed an indicator which measured the clustering degree of a graph.

In 2009, 391 documents from 52 different countries, with the expression of "Life Cycle Assessment," were published in international journals indexed in the ISI/Web of Science. The first publications, however, happened in the beginning of the 1990s, indicating that it is an emerging topic.

Although LCA studies have been realized, is it possible to say that there is already a scientific community in this area of knowledge? Is it possible to say that there are social interactions between the members of this scientific community? Taking the diffusion of LCA studies and the growth of scientific communities into consideration, the following questions can be posed: How are the LCA studies going to spread? How is the collaboration network between LCA researchers structured? And, finally, what are the characteristics of this network?

Based on a study covering 1,386 articles on life cycle assessment published in journals indexed in the ISI/Web of Science database until 2008, the aim of this paper is to show the dissemination of these studies and the collaboration network between researchers identifying:

1. The spread of knowledge of LCA considering the number of publications, subject areas, magazines, countries, institutions, and authors;
2. The configuration of this scientific collaboration network analyzing characteristics such as power law fitting, degrees of separation, giant component, and clustering.

Considering the premise that scientific articles contribute to development and consolidate values, methods, and judgments to be shared by a group of researchers and that the coauthorship reflects a social collaboration between researchers of a scientific community, the present study

Table 2 Main subject areas

Subject areas	Total
Environmental sciences	775
Engineering, environmental	650
Energy and fuels	155
Engineering, chemical	119
Environmental studies	70
Metallurgy	62
Engineering, civil	58
Construction technology	52
Thermodynamics	45
Materials science	37
Ecology	35
Engineering, mechanical	35
Agriculture, multidisciplinary	32
Engineering, manufacturing	31

Table 3 Total of countries per continent with articles and total of articles

Period	I		II		III		IV	
Years	1993–1996		1997–2000		2001–2004		2005–2008	
Continent	C	A	C	A	C	A	C	A
Europe	8	28	13	95	23	268	25	578
America	1	9	1	40	5	86	9	229
Asia	1	1	4	20	9	68	15	181
Oceania	1	1	1	2	2	23	2	27
Africa	0	0	1	2	3	7	5	14
No data	–	2	–	3	–	4	–	4

C countries, *A* articles

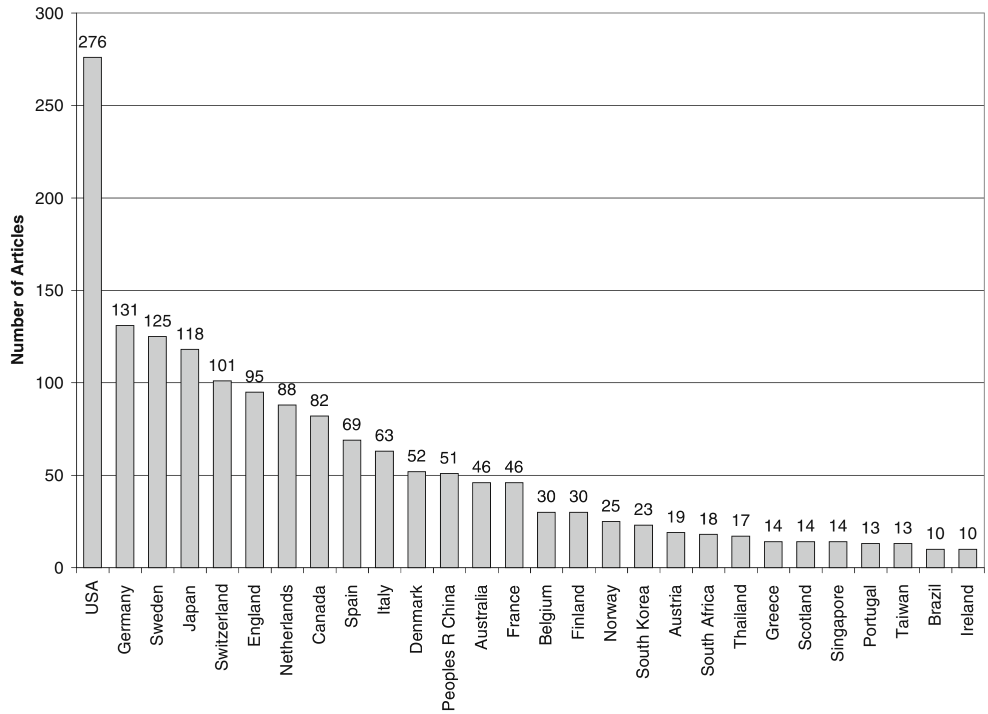

Fig. 1 Histogram of articles by country

intends to contribute to a better understanding of the organization of the scientific community of LCA around the world.

2 Methods

The research was based on a bibliometric approach of scientific articles published in international journals indexed in the ISI/Web of Science database related to "Life Cycle Assessment." The bibliometric approach offers a reasonable number of advantages. It is economical, accessible, and easy to implement. This approach also permits rapid intertemporal comparisons and is capable of examining a higher representation of the universe under investigation. In addition, it adapts well to international comparisons (Abramo et al. 2009).

The Web of Science was chosen because it is one of the more important and largest databases of scientific publications which has indexed more than 9,200 journals in science, social sciences, and arts and humanities being widely used for studies of a similar nature. It is also used as a reference for the construction of indicators of scientific production worldwide being associated with the generation of one of the main impact factor of journals, the Journal Citation Report.

In this study, scientific articles containing the words "life cycle assessment" published until the year 2008 were analyzed. The search covered the following databases: the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The analysis sample of this study was formed by the recovery of 1,386 articles.

As the first articles, within the universe, were published in 1993, additional queries were placed regarding four periods in order to identify the growth in the number of articles over time: period I, 1993/1996; period II, 1997/2000; period III, 2001/2004; and period IV, 2005/2008. The results recovered were also refined by subject areas, source titles, countries, institutions, and authors.

A free software, Pajek, which is normally employed for the representation and analysis of social networks, was used

Table 4 Increase of coauthorship in incidence and length in LCA publications

Period Years	I 1993–1996	II 1997–2000	III 2001–2004	IV 2005–2008
Articles	41	147	370	828
Single-authored	13	29	56	69
Coauthorship	28	118	314	759
Incidence (%)	68.3	80.3	84.9	91.7
Length	2.68	2.54	2.99	3.34

for the construction of the scientific collaboration network based on coauthorship. Each vertex of the network represented an author, and each edge indicated a coauthorship relation.

3 Results and discussion

3.1 Spread of knowledge about LCA

The spread of knowledge can be measured by the growth in the number of scientific articles published in international journals. In 1993, the first four articles on LCA were published in journals indexed in the ISI/Web of Science. In 2008, this number had increased to 243 publications. Comparing periods I and IV, the number of articles has increased 20.2 times; the subject areas, 3.2 times; the journals, 6.2 times; the countries, 5.0 times; the institutions,12.0 times; and, finally, the authors, 15.3 times. Table 1 illustrates the dissemination of LCA studies considering the four periods analyzed.

It is worth mentioning that the growth in the number of articles published is a phenomenon common to many areas of knowledge (Acedo et al. 2006; Laband and Tollison 2000). In the same period (1993–2008), the number of subject areas and journals indexed in the databases used in this study also increased. As an emerging issue, LCA's growth rates reflect its dissemination into the scientific community.

Table 2 lists the 14 subject areas of knowledge with at least 30 articles on LCA published in the ISI/Web of Science database. It is also important to say that these subject areas result from the journals index and not from the index of each individual article. The same journal can be indexed in more than one area.

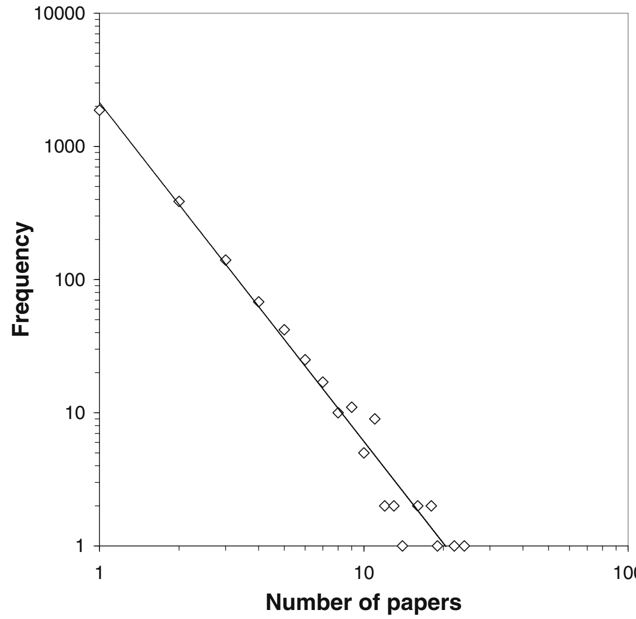

Fig. 2 Distribution of the number of papers written by scientists in LCA. Data are well fitted by a power law, $y=2,134.3\times z^{-2.544}$ ($R^2=0.9704$)

Although some areas listed in Table 2 are directly related to environmental issues, it can be observed that many journals indexed in other areas with specific technical focus, such as metallurgy and metallurgical engineering, thermodynamics, mechanical engineering, and manufacturing engineering, publish articles on LCA as well. This result may be an indicator of a greater awareness and dissemination of the LCA studies, which is forthcoming, considering that LCA has wide applicability and should be researched by several fields of knowledge.

It can be suggested that there was a process of internationalization which was originated with the first publications of authors in developed countries, mainly Germany and USA, contributing with ten and nine articles, respectively. In period I, the continents of Asia and Oceania were represented by Japan and Australia. Other countries had publications on LCA in period II, including emerging economies such as South Korea, Singapore, South Africa, and Taiwan. In period III, according to the database used in

Table 5 Summary of basic results of the articles about LCA

Articles	1,386
Single-authored papers	167
Coauthorship papers	1,219
Two-authored papers	372
Three-authored papers	386
Four authored papers	252
Multi-authored papers	209
Total number of authors	2,598
Mean papers per author	0.53
Mean authors per paper	1.87
Size of giant component	955
As a percentage	37%
Second largest component	26
Mean distance	6.5
Maximum distance	17
Clustering coefficient	0.753

Table 6 Power law of network properties

Item	τ	R^2
Papers per author	2.544	0.97
Authors per paper	2.495	0.75
Degree	2.198	0.88

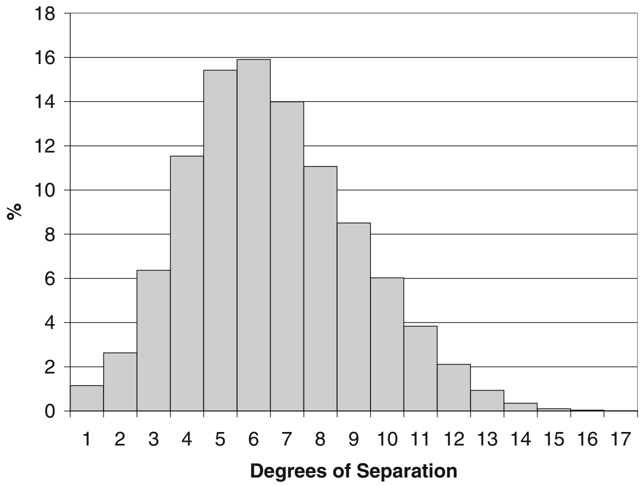

Fig. 3 Distribution of the degrees of separation between two authors (average=6.5)

this study, China, India, and Brazil published articles which have also contributed to the dissemination of LCA in Latin America. This process of spread continued in the following period (IV) incorporating other peripheral countries mainly in Latin America, Asia, and Africa. Table 3 shows the number of countries and articles in each continent considering the four periods analyzed.

Figure 1 displays not only the list of the countries with at least ten publications, but also the countries with the greatest number of publications on LCA. It can be verified that the developed countries constitute the vast majority although some emerging countries such as China, South Korea, South Africa, Taiwan, Singapore, and Brazil standout as well.

3.2 Scientific collaboration network about LCA

The practice of writing articles with multiple authors is relatively recent and has intensified in the last years. This phenomenon can be observed in the articles on LCA written during the four periods analyzed (Table 4).

In the case of LCA studies, a complementary research for the identification of specific causes for the increase of coauthorship would be interesting. Considering the four periods of analysis, the results showed that 1,219 articles (about 88% from the total) were written in collaboration as depicted in Table 5. Based on these coauthorship relations, it is possible to represent the social network of the LCA researchers by linking two scientists (vertices) if they coauthored a paper. In this study, a network was built with a total of 2,598 authors from the 1,386 articles obtained from ISI in order to understand the topological and dynamic characteristics of collaboration. A summary of the results can be seen in Table 5.

Interesting results from studies on social networks indicate that these networks follow certain properties and that they are not randomly structured. The results of the social network involving LCA researches are presented in sequence considering the following analyses: power law, degree of separation, giant component, and clustering.

3.2.1 Power law

In this study, it was verified that the articles' distribution per author follows a power law ($f(z)=2{,}134.3\times z^{-2.544}$),

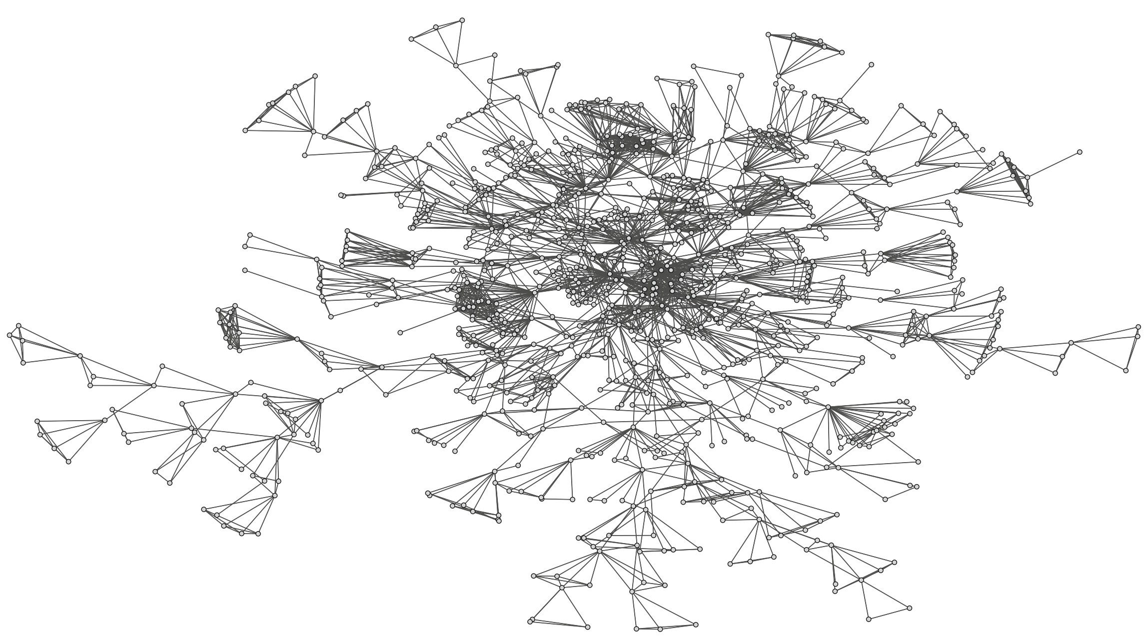

Fig. 4 The network's giant component with 955 vertices

with a high regression coefficient (R^2=0.9704). Figure 2 indicates that few authors of the social network involving LCA researches have many interactions with others while a great number of others have few interactions. It is interesting to notice that the exponent τ=2.544 found is very similar to the work of Albert et al. (1999) for WWW (τ=2.45). In spite of the lower R^2 coefficient, similar results of the degrees distribution and the number of authors per article were also verified (Table 6).

3.2.2 Degrees of separation

In the LCA coauthorship network, a similar result was found. The average distance between two authors taken at random was 6.5. Figure 3 shows the distance distribution confirming the collaboration of the small-world hypothesis on LCA.

3.2.3 Giant component

The appearance of a giant component with 955 vertices was verified (Fig. 4). The second largest component owns 26 vertices. This component embraces 37% of the network vertices. It is very likely that this component will increase embracing a larger percentile of authors in the near future.

3.2.4 Clustering

It was verified that the clustering degree of the LCA coauthorship network was high (0.753), therefore, coherent with other scientific communities (Newman 2001).

4 Conclusions

In spite of being an area with less than 20 years of publications registered in the ISI Web of Science, LCA is experiencing fast dissemination, involving a large number of articles, authors, and institutions. Nowadays, publications from 60 countries with a significant number of themes are available. It is worth mentioning that articles on LCA are found in periodicals of different areas such as mechanics, metallurgy, agriculture, and manufacture.

Taking into consideration the questions posed in Section 1, it is possible to say that the findings of the study indicate that the researchers that realize LCA studies form a scientific community with a similar graph structure of other communities analyzed in the literature about SNA.

Although there are researchers around the world from different countries and institutions, it is possible to observe social interaction between them. It can be observed through the giant component which embraces 37% of the authors, still a small number, nonetheless, one which may experience impressive growth in the near future. The proximity among researchers inside the community also can be seen through the average distance between authors which follows the small-world hypothesis.

LCA network also presents other properties verified in other networks of more consolidated academic collaboration such as: the resulting graph follows power law patterns for some properties, similar to nets as WWW, and it also presents a high degree of clusterability which is coherent with other scientific communities.

These findings can be complemented with new studies in order to better understand the organization of the LCA scientific community. It is possible, for instance, to apply other methodologies of SNA such as centrality indexes for the identification of main authors and the role played by each researcher into the community and to realize citation and co-citation analysis for the identification of relevant themes in relation to LCA. Furthermore, the analysis of patent documentation, which has appeared in recent years (por ex, Barker (2009); Yamamoto et al. (2009)), also offers great potential for further studies with the identification of technologies, competences, and business strategies related to LCA.

References

Abramo G, D'Angel C, Caprasecca A (2009) Allocative efficiency in public research funding: can bibliometrics help? Res Policy 38:206–215

Acedo F, Barroso C, Casanueva C, Galan J (2006) Co-authorship in management and organizational studies: an empirical and network analysis. J Manag Stud 43:957–983

Albert R, Jeong H, Barabasi A (1999) Diameter of the World-Wide Web. Nature 401:130–131

Balancieri R, Bovo A, Kern V, Pacheco R, Barcia R (2005) A análise de redes de colaboração científica sob as novas tecnologias de informação e comunicação: um estudo na plataforma Lattes. Ci Inf 34:64–77

Barabási A, Jeong H, Nda Z, Ravasz E, Schubert A, Vicsek T (2002) Evolution of the social network of scientific collaborations. Phys A 311:590–614

Barker S (2009) Employee life cycle management system for insurance company, has storing unit employee life cycle management data in database, and managing unit centrally managing management data to make management data to be available to employers. US Patent 2,009,198,521-A1

Cronin B, Shaw D, La Barre K (2003) A cast of thousands: co-authorship and subauthorship collaboration in the twentieth century as manifested in the scholarly literature of psychology and philosophy. J Am Soc Inf Sci Tech 54:855–871

Goldenberg J, Libai B, Muller E, Stremersch S (2010) The evolving social network of marketing scholars. Mark Sci 29:561–567

Goyal S, van der Leij M, Moraga-Gonzalez J (2006) Economics: an emerging small world. J Polit Econ 114:403–412

Hou H, Kretschmer H, Liu Z (2008) The structure of scientific collaboration networks in scientometrics. Scientometrics 75:189–202

Klöpffer W (2007) Publishing scientific articles with special reference to LCA and related topics. Int J Life Cycle Assess 12:71–76

Kretschmer H (2004) Author productivity and geodesic distance in bibliographic co-authorship networks, and visibility on the web. Scientometrics 60:409–420

Kuhn T (2006) A estrutura das revoluções científicas trad Beatriz Boeira, 9th edn. Sao Paulo, Perspectiva

Laband D, Tollison R (2000) Intellectual collaboration. J Pol Econ 108:632–662

Lee S, Bozeman B (2005) The impact of research collaboration on scientific productivity. Soc Stud Sci 35:673–702

Mattedi M, Spiess M (2010) Modalidades de regulação da atividade científica: uma comparação entre as interpretações normativa, cognitiva e transacional dos processos de integração social da comunidade científica. Educ Soc 31:73–92

Milgram S (1967) Small-world problem. Psy Today 1:61–67

Newman N (2001) The structure of scientific collaboration networks. PNAS 98:404–409

Newman N, Watts D (1999) Scaling and percolation in the small-world network model. Phys Rev E 60:7332–7342

Oliveira E (2005) Produção científica nacional na área de geociências: análise de critérios de editoração, difusão e indexação em bases de dados Ci. Inf 34:34–42

Watts D, Strogatz S (1998) Collective dynamics of smallworld networks. Nature 393:440–442

Yamamoto N, Aoyagi Y, Hitachi L (2009) Design support system for supporting environmental impact assessment of product life cycle, has life cycle inventory data registration processing portion for performing process for referencing life cycle inventory data. US Patent 2,009,083,333-A1

Yan E, Ding Y, Zhu Q (2010) Mapping library and information science in China: a coauthorship network analysis. Scientometrics 83:115–131